Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

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DOCUMENTATION OF CATHENA INPUT FILES FOR THE APOLLO COMPUTER

by

Atomic Energy of Canada Limited
Whiteshell Nuclear Research Est.
Pinawa, Manitoba

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Documentation of CATHENA input files for the APOLLO Computer

Prepared by Atomic Energy of Canada Limited

ABSTRACT

Input files created for the VAX version of the CATHENA two-fluid code have been modified and documented for simulation on the AECB's APOLLO computer system. The input files describe the RD-14 thermalhydraulic loop, the RD-14 steam generator, the RD-12 steam generator blowdown test facility, the Stern Laboratories* Cold Water Injection Facility (CWIT), and a CANDU™ 600 reactor. Sample CATHENA predictions are given and compared with experimental results where applicable.

* formerly Westinghouse Canada

RÉSUMÉ

Les fichiers d'entrée créés pour la version VAX du programme de calcul de deux fluides, CATHENA, ont été modifiés et documentés pour la simulation sur le système informatique APOLLO de la CCEA. Ces fichiers décrivent la boucle thermohydraulique de RD-14, le générateur de vapeur de RD-14, l'installation d'essais de purge du générateur de vapeur de RD-12, l'installation d'Essais d'Injection d'Eau Froide (EIEF) (CWIT) de Laboratoires Stern* et un réacteur CANDU-600. On donne et compare les résultats types des calculs par CATHENA avec les résultats des essais s'il y a lieu.

* Autrefois Westinghouse Canada

DISCLAIMER

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EXECUTIVE SUMMARY

The purpose of this work, performed for the Atomic Energy Control Board (AECB) was to convert and document selected CATHENA input files for use on the AECB's APOLLO computer. Simulations of a number of thermalhydraulic experiments and the CANDU™ 600 heat transport system may be performed using these input files.

CATHENA, created at AECL, is an advanced, one-dimensional thermalhydraulic computer code developed primarily to analyze postulated loss-of-coolant-accident (LOCA) scenarios and upset conditions for CANDU™ nuclear reactors. The code uses a non-equilibrium, two-fluid thermalhydraulic model to describe fluid flow. Component models describing the behaviour of pumps, valves, steam separators and discharge through breaks are available to complete the idealizations of reactor systems.

A large number of component and integral tests have been designed to investigate the thermalhydraulic behaviour of the CANDU™ heat transport system under upset and accident conditions. The data from these tests are used to validate analysis tools and methods used in LOCA calculations. In particular, CATHENA has been verified against many of these experiments. Also, CATHENA has been used to model large-break LOCAs in the CANDU™ 600 reactor.

The CATHENA input files documented under this contract may be used to simulate

1) tests performed in the RD-14 test facility studying thermosiphoning, small inlet header breaks, critical inlet header breaks, outlet header breaks, and flow stability;
2) steam generator characterization and blowdown tests;
3) cold water injection tests; and
4) a CANDU™ 600 reactor to study large-break loss-of-coolant scenarios.

These files, installed on the AECB APOLLO computer, will allow AECB staff to perform simulations with the CATHENA code and will help to familiarize them with two-fluid calculations obtained from a thermalhydraulic computer code. The "homogeneous" assumption used for thermalhydraulic analysis performed to support many CANDU™ licensing calculations can be checked using the CATHENA two-fluid code.

This report describes input files, prepared for CATHENA, which are more fully documented in the AECL/AECB proprietary reports WNRE-RC-54-1 to WNRE-RC-54-5. Sample results obtained by "running" these input files for an experiment are compared with experimental results. Agreement is generally very good, demonstrating the predictive capability of the code.

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A. INTRODUCTION

1. Background

Part of the Atomic Energy Control Board's (AECB) mandate is to reviev safety licensing submissions, and assess the validity of any analysis that has been performed. In many cases, thermalhydraulic analysis of events during a postulated loss-of-coolant accident (LOCA) or upset scenario is presented.

It is important that AECB staff have access to advanced "tools" with which they can check the analysis. The CATHENA code offers this capability.

CATHENA[1] has been validated under a wide range of conditions and thus confidence may be placed on predictions made when simulating postulated events in the CANDU™ system. Also, because of the flexible input arrangement used by CATHENA, sensitivity studies can be easily performed. Finally, use of the CATHENA code will help AECB staff gain experience with two-fluid thermalhydraulic phenomena predicted by the code.

Current licensing calculations are performed using homogeneous thermalhydraulic codes (e.g., FIREBIRD[2], SOPHT[3]). CATHENA, a full two-fluid code, has the ability to check under which conditions a "homogeneous" assumption is valid, and under which conditions it "breaks down". This is particularly important in the study of Emergency Core Coolant (ECC) performance when "separated" flow is expected to exist in the reactor primary circuit.

It should be noted that the international trend is towards thermalhydraulic analysis using two-fluid codes (RELAP[4], TRAC[5], CATHARE[6], etc.).

2. Purpose of CATHENA Input Files

In 1986 December, CATHENA was installed on the AECB APOLLO computer by WARDROP Engineering Consultants (contract 87055-6-4087/01-SS). However, only three "test" cases were provided with the installation, to assure that the VAX to APOLLO conversion was performed correctly.

During the development and validation of CATHENA, a large number of input cases (or input files) were created. In many cases, no formal documentation was generated, although a substantial investment in manpower and computer resources was required.

The purpose of this contract is to provide many of these files, complete with documentation, to the AECB to execute on the AECB's APOLLO computer. Thus AECB staff would have access to these validation and reactor input files without the investment of the manpower required to generate the files.

These input files will be used to familiarize AECB staff with the CATHENA two-fluid code, the manner in which a test facility/reactor is idealized or modelled, and the interpretation of the simulation results. Also, the CANDU™ 600 file will allow AECB personnel to perform certain reactor-typical calculations.

3. Scope of Contract

The CATHENA input files, previously developed by Atomic Energy of Canada (AECL), are to be delivered and documented under the terms of this contract. Thus the scope of the contract includes only the documentation of the files, and installation on the APOLLO computer - not development costs.

4. Contract Identification

This work was produced by AECL under contract to the Atomic Energy Control Board (AECB); AECB project number 2-152-1.

B. CATHENA CODE

1. Numerics

CATHENA is an advanced, one-dimensional thermalhydraulic computer code developed primarily to analyze postulated loss-of-coolant-accident (LOCA) scenarios and upset conditions for CANDU™ nuclear reactors. The code uses a non-equilibrium, two-fluid thermalhydraulic model to describe fluid flow. Provision is also made for modelling a non-condensible gas in the vapour phase. Conservation equations for mass, momentum and energy are solved for each phase (liquid and vapour), resulting in a 6-equation model (7 if a non-condensible is present). Interphase transfer of mass, momentum and energy is calculated using a set of flow-regime-dependent constitutive relations. As well, flow-regime-dependent constitutive relations for wall shear specify momentum transfer between the fluid and the pipe surfaces.

The numerical solution method used is a staggered-mesh, semi-implicit, finite-difference method that is not transit-time-limited[7]. Conservation of mass is achieved using a truncation error correction technique similar to that used in RELAP5/MOD2[4].

Heat transfer from metal surfaces is handled by a comprehensive wall heat transfer package. A set of flow-regime-dependent constitutive relations specifies energy transfer between the fluid and the pipe wall and/or fuel element surfaces. Heat transfer by conduction within the piping and fuel is modelled in the radial direction and can be modelled in the circumferencial direction as well. Radiative heat transfer and the zirconium-steam reaction can also be included. Built into this package is the ability to calculate heat transfer from individual groups of pins in a fuel bundle subjected to stratified flow. Under these conditions, the top pins in a bundle are exposed to steam while the bottom pins are exposed to liquid.

Component models describing the behaviour of pumps, valves, steam separators and discharge through breaks are available to complete the idealizations of reactor systems. A more complete description of the CATHENA code is available in reference 1.

Control systems in CANDU™ reactors (e.g., boiler level/pressure control) can be quite complex and are modelled in many other thermalhydraulic codes, such as SOPHT and FIREBIRD, as specialized Fortran routines. In CATHENA, a generalized system has been developed in which control systems are described by user-supplied input data[8].

One of the primary goals in the CATHENA development program is to maintain a generalized "user-friendly" input approach, in which the user models a reactor or test facility using only input data. Thus, only one version of the code is required.

CATHENA was developed by Atomic Energy of Canada Limited (AECL) at the Whiteshell Nuclear Research Establishment (WNRE) using a VAX 8650 computer system. It consists of over 75000 lines of FORTRAN executable statements (about 650 subroutines).

2. Validation

The CATHENA code has been extensively validated using experimental data from the RD-12 and RD-14 thermalhydraulic loops[9,10], the Westinghouse Cold Water Injection (CWIT) Facility[11], and other experimental facilities. As well, the code has simulated a number of LOCA and upset conditions that occurred in an actual CANDU™ plant[12]. The CATHENA calculations showed excellent agreement with plant data.

3. Host Computers

CATHENA was developed on a Digital Equipment Corporation (DEC) VAX 8650 computer using the VMS operating system. However, the code is written in "standard" FORTRAN-77 and has been installed on the APOLLO, CDC, and FPS computers.

Currently, a trend is seen in which larger codes (such as CATHENA) are being installed on smaller super microcomputers with virtual memory systems such as the micro-VAX and APOLLO systems. These computers can be purchased for about $20k. Although the computing speed of these computers may only be less than 10% of a large mainframe computer, an "overnight run" can complete a complex simulation. Thus in many cases, it may be more economical to purchase a super microcomputer rather than purchase computer resources from a vendor. This has been reported in reference 13, prepared by the AECB.

C. RD-14 FACILITY

1. Introduction

A major emphasis in the CATHENA validation program has been to simulate selected RD-14 experiments. This section documents selected CATHENA idealizations used by the Thermalhydraulics Branch at WNRE to simulate tests conducted in the RD-14 Test Facility. Generally, these idealizations can be used to simulate the blowdown, thermosiphoning and flow stability experiments conducted from 1985 February to 1987 May.

Since the commissioning of RD-14 in 1985, selected experiments from several test series have been simulated using CATHENA. In most cases more than one experiment in a test series was simulated. A sample listing of an input file from each test series simulated using CATHENA can be found in the AECB-AECL proprietary report WNRE-RC-54-1.

2. Facility

2.1 Background

The CANDU™ Owners Group (COG), through the CANDEV program, conducted experiments in RD-14 that provided the data needed to understand important thermalhydraulic phenomena and to validate computer models. In the past, data for code validation have been obtained from small-scale pressurized-water loops. To study the non-equilibrium effects, however, required a large-scale facility. To meet this requirement and to provide a better understanding of the transient behaviour of reactor cooling systems, the design of a large-scale pressurized water loop, designated RD-14, was undertaken in 1981 at WNRE. Construction started in the spring of 1982 and experimental testing began early in 1985.

2.2 General Description

Although most of the loop was scaled to a CANDU™ 600 reactor, provisions were made to allow simulation of other CANDU™ plant designs. What follows is a brief, system by system, description of the RD-14 facility, shown schematically in Figure 1. A more detailed description of each system is available in reference 10.

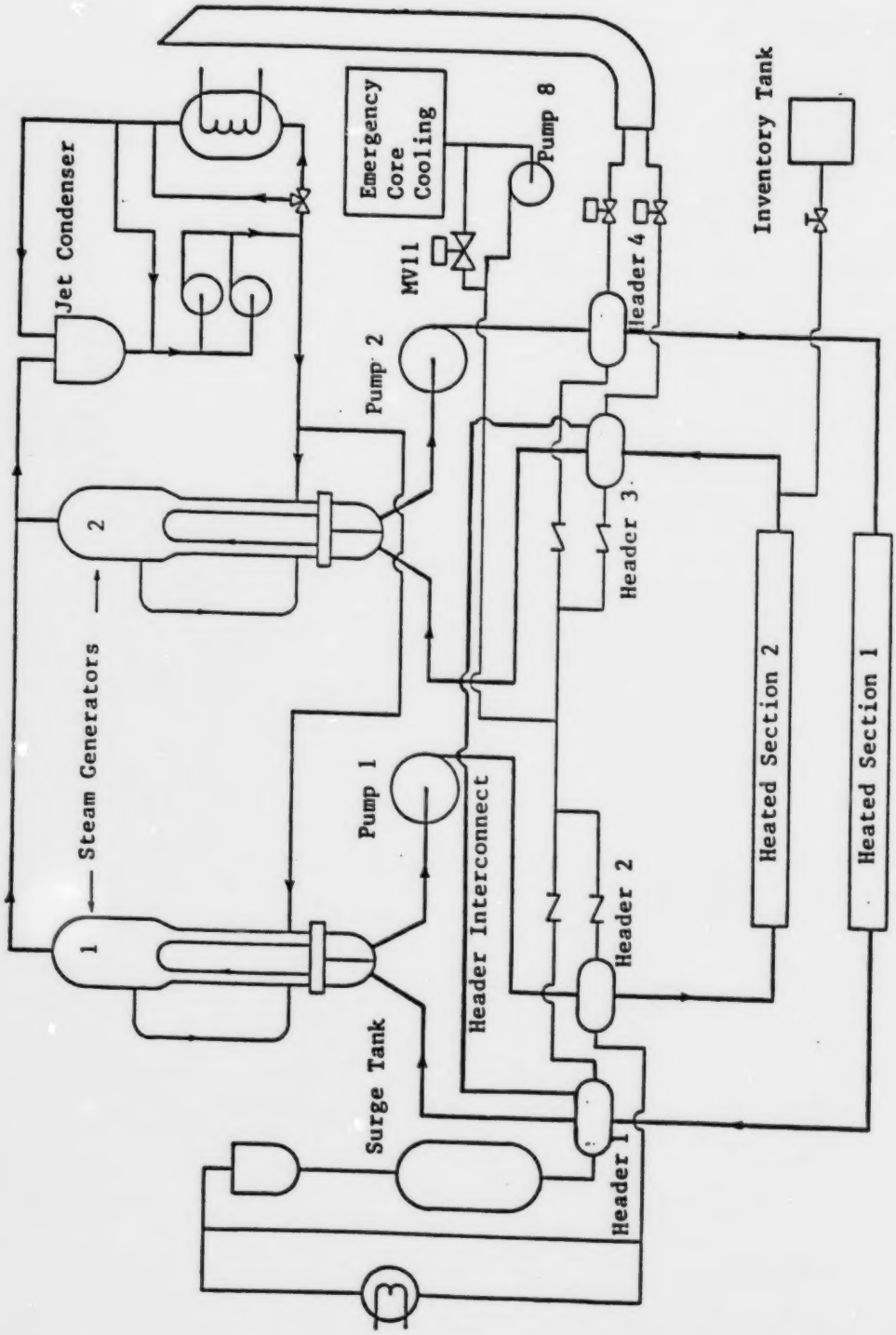

Figure 1: RD-14 Loop Schematic

2.2.1 Primary Side

The RD-14 reference design was chosen so that conditions of fluid mass flux, transit time, pressure and enthalpy in the primary system would be very similar to those in a typical reactor under both forced and natural circulation. It has the basic figure-of-eight geometry of a CANDU™ reactor, with a single horizontal 5.5-MW channel per pass and a 1:1 scaling of the vertical elevations throughout the loop. Each 6-m-long channel contains 37 electrically heated fuel-element simulators of almost the same heat capacity as reactor fuel, connected to end fitting simulators. The single channel per pass alloved for full-sized channel and feeders in each pass with the remainder of the loop, i.e., pumps, steam generators, etc., sized accordingly. Preserving the 1:1 vertical scaling maintained similar hydrostatic pressures between RD-14 and a full-sized reactor. Loop piping above the headers was sized so that the axial lengths and pressure drops were approximately equal to the full-scale system. The steam generators were also scaled approximately 1:1 with those of a typical CANDU™ steam generator in terms of tube diameter, mass flux and heat flux, to achieve reactor-like conditions within them. Primary fluid circulation is provided by two high-head centrifugal pumps, which generate channel flov rates similar to a single reactor channel.

Primary side pressure is controlled by a surge tank equipped with an electrical heater.

Both inlet and outlet header breaks can be produced using the blowdown system. Loop coolant is ejected from the loop into the blowdown stack and discharged to atmosphere. A variety of orifice plates can be placed immediately ahead of a fast-acting valve to simulate a range of break sizes.

Major loop parameters of RD-14 and a typical reactor are shown in Table 1.

2.2.2 Secondary Side

Other than the steam generators, no attempt was made to scale the secondary side components to a reactor. Sizing was based on operational considerations only, i.e., to remove up to 5.5 MW of heat from each steam generator.

The RD-14 steam generators are recirculating U-tube type with internal pre-heaters and external downcomers. Generally, the steam generators were scaled approximately 1:1 with the reactor steam generators in terms of individual tube diameter, heat flux and vertical height. In 1986 October, steam separators were added to the steam generators to make them more reactor-typical in operation. Table 1 shows a comparison of the RD-14 steam generators and a typical reactor steam generator.

Secondary side pressure is controlled by a jet condenser in which steam is condensed by contact with cold water. The condensate is mixed with cold water. Some of the mixture is returned to the steam generator as feedwater, the rest is returned to a heat exchanger to be cooled.

Table 1: RD-14 Characteristics Compared to a Typical Reactor

Characteristic	RD-14	Typical Reactor
Operating Pressure (MPa)	10	10
Loop Volume (m^3)	0.9514	57.0
Loop Piping I.D. (m)	0.074	varies
Heated Sections:	indirect heated 37-rod bundles	nuclear fuel 37-element bundle
Length (m)	6	12 x 0.5
Rod diameter (m)	0.0131	0.0131
Flow tube diameter (m)	0.1034	0.1034
Power (kW/channel)	5500	5410
Pumps:	single stage	same as RD-14
Impeller diameter (m)	0.381	0.813
Rated flow (kg/s)	24	24 (max/channel)
Rated head (m)	224	215
Specific speed	565	2000
Steam Generators:	recirculating U-tube	recirculating U-tube
Number of tubes	44	37/channel
Tube diameter I.D. (m)	0.01363	0.01475
Secondary heat-transfer area (m^2)	41	32.9/channel
Heated Section-to-Boiler Top Elevation Difference (m)	21.9	21.9

2.2.3 Emergency Coolant Injection

The RD-14 emergency coolant injection (ECI) system can be used to represent the three modes of ECI found in CANDU™ reactors, i.e., high-pressure phase, low-pressure recovery phase, and gravity feed in case of pump failure. The system was also designed to simulate various plant configurations.

High-pressure injection is achieved by pressurizing the ECI tank with nitrogen and discharging the ECI flow through MV11 (see figure 1). This represents the pressurized-tank injection typical of CANDU™ 600 and Bruce stations.

Low-pressure injection is simulated by pumping water from the distilled water storage tanks using pump 8.

Gravity feed can be simulated by draining the distilled water tanks without the assistance of the injection pump.

The actual flow rate and distribution of emergency coolant is determined by the size and location of the break. Orifices in the injection lines provide scaled simulation of reactor injection flow rates.

2.2.4 Header Interconnect

The RD-14 header interconnect was designed to represent either the CANDU™ 600 or Darlington Nuclear Generating Station interconnect geometries. The interconnect was designed to be geometrically and hydraulically similar to those two interconnect geometries. This was essentially the design basis used for the rest of the RD-14 facility. Table 2 compares the CANDU™ 600 RD-14 header interconnect geometry with the actual CANDU™ 600 reactor header interconnect.

Flow through the header interconnect lines can be adjusted, using orifices, to give reactor-typical flows.

Changes were made to the header interconnect geometries in 1987 to improve the similarity with the reactor interconnects. Tests conducted in 1986 had the interconnect lines connected directly to the outlet headers and one flow-restricting orifice location. Tests conducted beginning in 1987 had the interconnects attached to the primary pipework connecting the headers to the steam generators. An additional flow orifice location was added close to header 3. Minor piping alterations were also made to facilitate additional instrumentation.

3. CATHENA Idealization

3.1 Philosophy

The idealizations in this section were designed to be used for the three types of primary heat transport system (PHTS) events previously mentioned. They represent a compromise between a "fine" nodalization, which would be better able to capture details of the experiments at the expense of computer time; and a "coarse" nodalization, which may not be able to capture details of the experiments but would be fast running. Clearly, for experiments that run for thousands of seconds (i.e., thermosiphoning experiments), a very detailed idealization could be cost-prohibitive to run.

Table 2: Comparison of CANDU 600 and RD-14 Header Interconnect Designs

Parameter	CANDU 600	RD-14
Length (m)	32.0	32.0
Flow Area (m^2)	0.0167	0.000176
Internal Diameter (m)	0.146	0.015
Height (m)	5.50	5.50
K factor	86.0	47.7

The detail offered by the breakdown of branches and wall models in the idealization should be adequate for most scenarios to be simulated. The number of nodes used both in the thermalhydraulic branches and heat transfer wall models should be viewed as a guide, however. Converged solutions do not necessarily result from this number of nodes. The user may require additional nodes in certain places in the idealization depending on the type of scenario being simulated and the detail required.

The three idealizations presented here are 1) the RD-14 primary side, including the surge tank and connecting pipework; 2) the emergency coolant injection system; and 3) the header interconnect system. Generally, for the types of accident scenarios covered in this report, the RD-14 secondary side has been successfully modelled as boundary conditions. There is some evidence[14], however, that in a very limited number of cases, the thermal feedback between the primary and secondary side may be required. This would preclude modelling them simply as boundary conditions.

3.2 Primary Side

The RD-14 primary side and the CATHENA idealization described in this subsection are shown in Figures 2 and 3. The primary side consists of all the RD-14 primary side piping connecting the headers, heated sections, steam generators, pumps and surge tank. It does not include the blowdown lines exiting the headers. In cases where these lines are used (i.e., header blowdowns), a break model is applied to the appropriate header and a constant boundary condition pressure of one atmosphere is assumed to exist downstream of the break location.

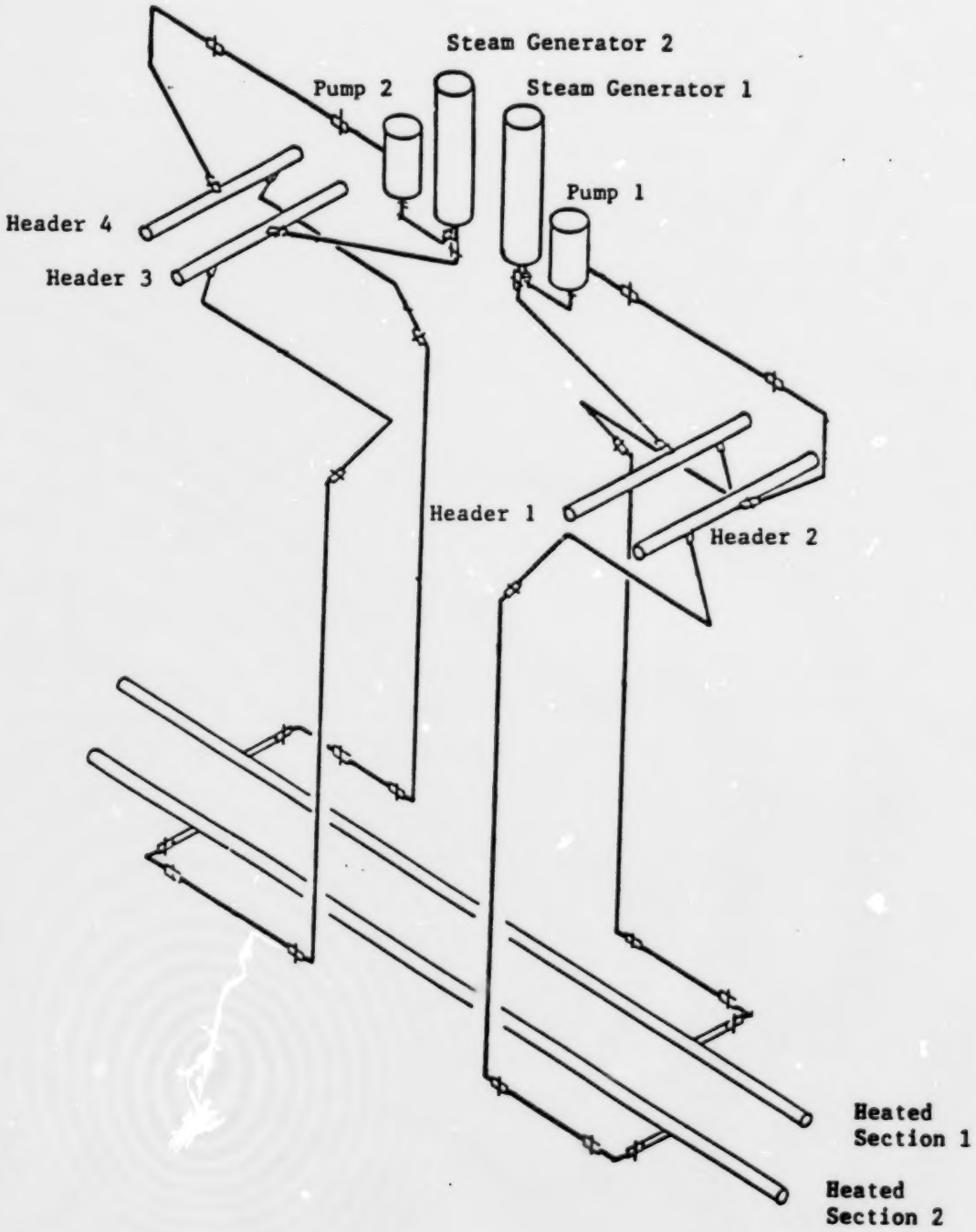

Figure 2: RD-14 Primary Side

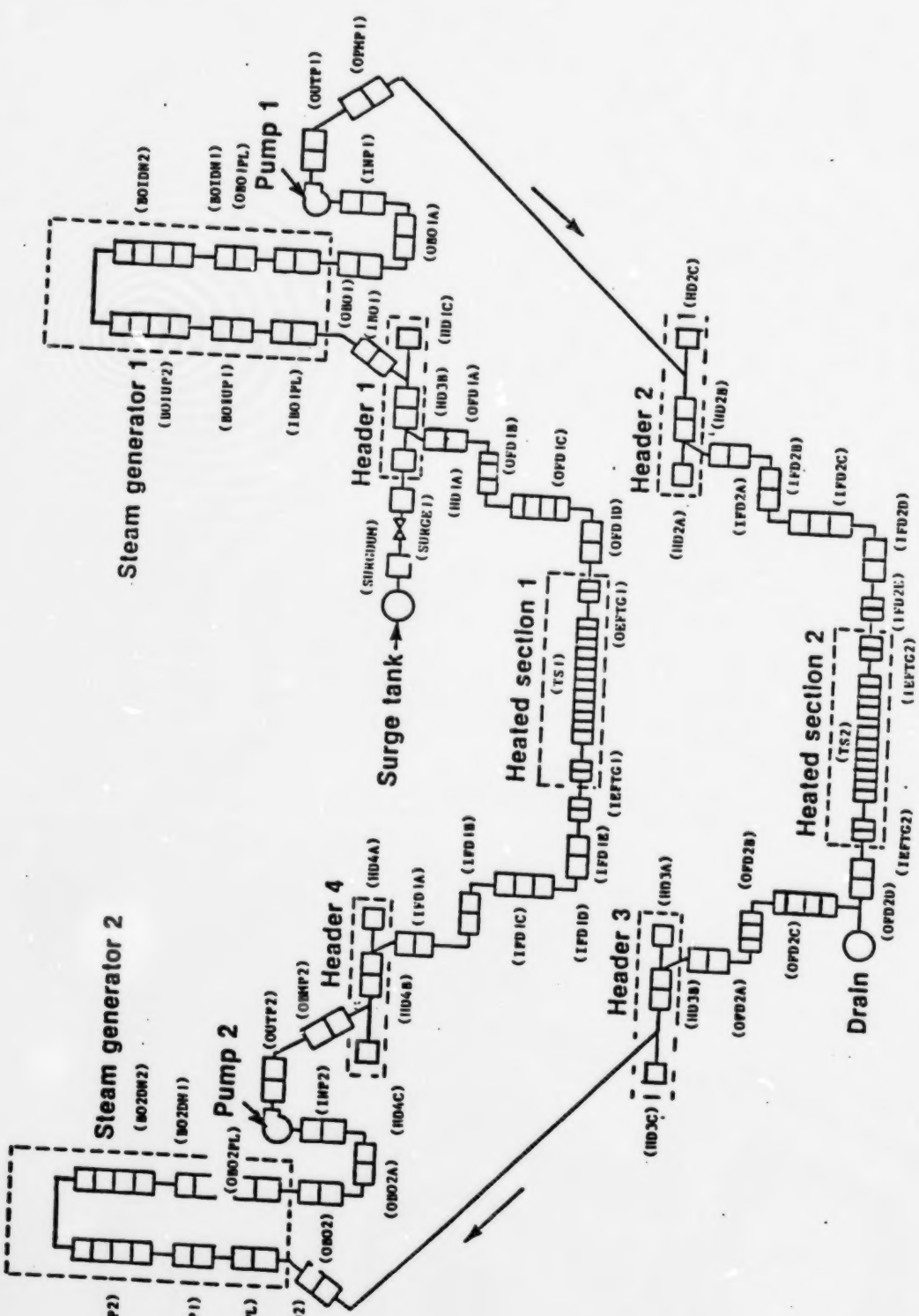

Figure 3: CATHENA Idealization of RD-14 Primary Side

3.3 Thermalhydraulic Idealization

The primary side idealization was developed by ensuring that the volume, length, flow area and elevation change of each branch resemble as close as possible the RD-14 facility. This ensures the correct transit time and hydrostatic head of the fluid. Since CATHENA is a two-fluid code, horizontal and vertical sections of piping generally are not lumped together as one inclined branch, unless the horizontal or vertical section is very short. Sections of piping that are inclined but vary in the degree of inclination can be lumped together to simplify the idealization.

The flow areas of complicated geometries, such as the end fittings, boiler plenums, and pumps were determined by dividing the volume of the device by the flow path length. This method proved acceptable, provided the flow area, and hence fluid velocity, was not significantly different from what would occur in the facility. Modelling of the headers using this procedure to account for the dead end volumes was not acceptable for just this reason. The dead volumes at the ends of the headers were modelled, therefore, as separate branches with one closed end.

The total volume of the primary side idealization has been compared to the volume of the facility and found to be within 1%. This volume does not include the surge tank or the line connecting it to the primary loop.

Summing of minor losses (for elbows, tees, valves, etc.) proved both arduous and insufficient to arrive at the same pressure losses as those observed in the facility. Undoubtedly, many intrusions into the flow path (i.e., fluid temperature measuring devices) exist that are difficult to account for. Complicated geometries add another difficulty in using handbook values for minor losses. Loss coefficients were determined from RD-14 tests. Pressure drop data from several steady-state single-phase liquid flow tests at various flow rates and temperatures were examined. For simple area changes between branches, the pressure drop calculated internally by CATHENA was correct; however, for more complicated junctions (steam generator plenums), junction resistances were applied to achieve a more correct pressure drop.

4. Input Files

4.1 Introduction

One of the objectives of the RD-14 thermalhydraulic research program is to perform integrated full-system experiments to identify and to investigate thermalhydraulic phenomena associated with the CANDU™ heat transport system (HTS) under various postulated events. Three types of postulated events are included in this report: 1) thermosiphoning, 2) blowdown, and 3) flow stability.

Selected experiments from several test series have been simulated using CATHENA. Each of the test series from which a CATHENA simulation has been made, is described separately below. A fully documented input file for each of these tests has been provided to the AECB.

4.2 Thermosiphoning

In certain postulated accident conditions in a CANDU™ nuclear reactor, the primary coolant pumps are tripped following shutdown of the reactor. Heat removal from the core is then by natural circulation, or thermosiphoning, of the primary coolant. In some cases, void can appear in the primary heat transport system either because of primary coolant shrinkage due to cooldown or because of a small-break loss-of-coolant accident. Under these conditions, thermosiphoning can occur in a two-phase mode. It is important to ensure that decay heat can be adequately removed in this situation.

In 1985 March and April and again in 1986 May tests were performed in the RD-14 facility to examine the thermosiphoning flow behaviour as a function of system mass inventory. Each test was begun once stable, single-phase, natural circulation of the primary fluid was established. Controlled intermittent draining of the primary fluid induced void generation and the test continued until the power was tripped by high fuel-element-simulator (FES) temperatures. Test parameters that were altered included the primary power, secondary pressure and initial primary pressure. Simulations of selected thermosiphoning test were performed with CATHENA and are reported in reference 14.

4.3 Small Break Tests

A series of tests was conducted in RD-14 to investigate the thermalhydraulic consequences of a feeder-sized break located at an inlet header. The break diameter used for these tests was 7 mm, which scales to the cross-sectional area of two feeders for a CANDU™ reactor loss-of-coolant accident. The break was located at inlet header 4. All tests started from the steady-state conditions of full power (5 MW per pass), full flow (21 kg/s), and nominal reactor outlet header pressure (10 MPa). The secondary side pressure was set to 4.5 MPa and the emergency coolant injection (ECI) system (for those tests with ECI) was set to 5.5 MPa for the high-pressure ECI and 1.3 MPa for the low-pressure ECI.

The series included tests with and without ECI, with and without pump speed rampdown, to simulate loss-of-class IV power; with and without surge tank isolation; and with and without secondary side depressurization.

Shown in Figure 4 is the CATHENA prediction of sheath temperatures of the fuel element simulators (FES). A top FES and bottom FES are shown and compared to experimental results. Note that for a test in this series the experiment shows the top pin to rise in temperature at about 200 s while the bottom pin remains cool. This indicates that stratified flow existed in the channel. CATHENA correctly predicted this phenomena.

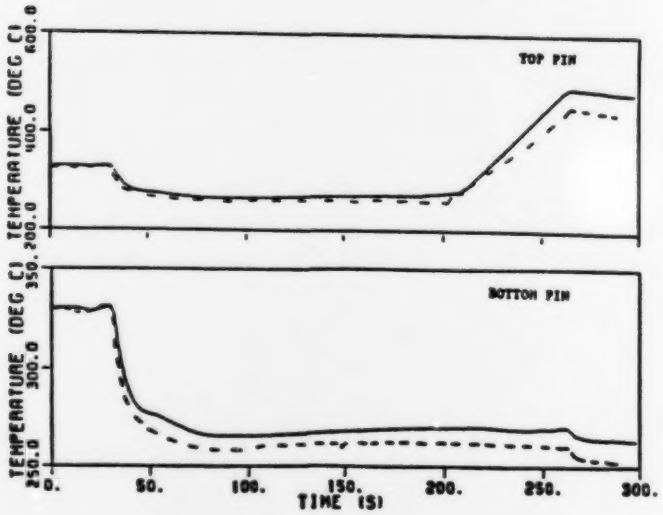

Figure 4: Mid Channel FES Sheath Temperatures for Small Break Test

4.4 Critical Inlet Header Break Tests

A critical break in the primary heat transport system of a pressurized-water reactor can be defined as the break size that results in the primary circuit pumping forces being balanced by the hydraulic forces through the break. When this happens, flow stagnation in the channel downstream of the break occurs. If the flow remains stagnated for a prolonged period of time, fuel damage can result.

In 1987 February and March a series of tests was conducted to investigate the thermalhydraulic consequences of such a break at an inlet header, and to assess the effectiveness of the ECI system in cooling the fuel-element simulators. CATHENA was used to predict the critical break size prior to the test series being conducted. Break sizes were then chosen that were larger than the predicted critical break size, smaller than the predicted critical break size and at the predicted critical break size. Experiments were performed with primary pumps running and also with primary pump speed rundown to simulate a loss of class IV power.

All tests started from steady-state conditions of full power (5 MW per pass), full flow (21 kg/s), and nominal reactor pressure (10 MPa). The secondary side pressure was set at 4.5 MPa, the high-pressure ECI system was set to 5.5 MPa and the low-pressure ECI was set at 1.5 MPa.

Shown in Figure 5 is the CATHENA predicted system pressure for a critical inlet header break in RD-14. Also shown is the predicted injection flow to a header. Agreement with experiment is seen to be very good. A more detailed description of this CATHENA simulation is given in reference 15.

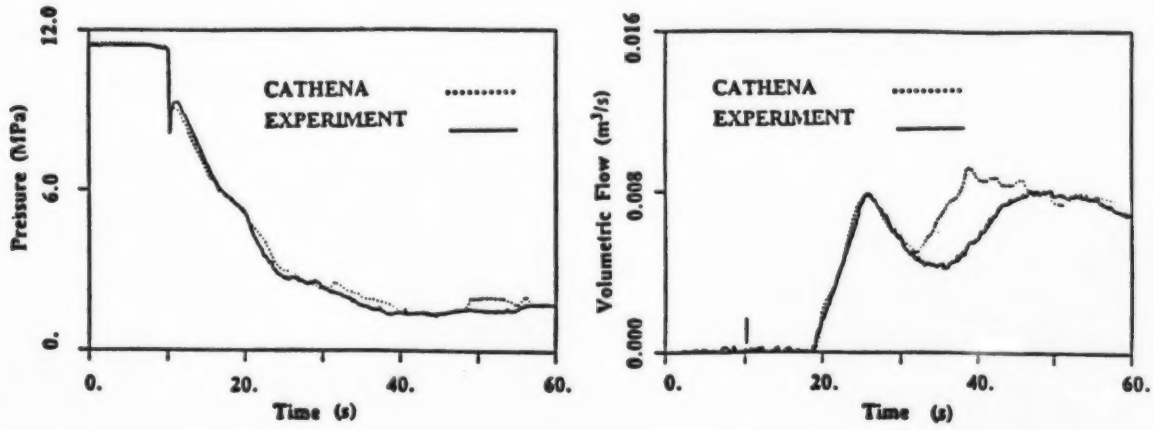

Figure 5: CATHENA Predictions for Critical Inlet Header Break

4.5 Outlet Header Break Tests

This series of tests was designed to study the thermalhydraulic behaviour of a CANDU™-type heat transport system during blowdown (from an outlet header), and injection phases of a loss-of-coolant accident. This test series covers the range of outlet header break sizes from the critical break size (approx. 35 mm for RD-14) to a guillotine, or large break (52 mm for an outlet header). As well as varying the break size, tests were also conducted with and without pump speed rundown to simulate loss of class IV power.

As in other break tests, these tests started from steady-state conditions of full power (5 MW per pass), full flow (21 kg/s), and nominal reactor pressure (10 MPa). The secondary side pressure was set to 4.5 MPa, the high-pressure ECI system was set to 5.5 MPa.

A description of a CATHENA simulation of a large outlet header break is given in reference 16.

4.6 Flow Stability Tests

This section applies to all flow stability tests conducted in 1986 and 1987.

Current CANDU™ reactors are designed to operate with up to 4% steam quality at the outlet headers of the primary heat transport system. When operated with net quality at the reactor outlet header, the reactor PHTS may exhibit flow and pressure oscillations. These potential oscillations may be eliminated by installing pipework connecting the outlet headers. This has been done with current CANDU™ reactors.

Tests were conducted in the RD-14 facility to examine the primary heat transport system flow stability behaviour with a header interconnect connecting outlet headers 1 and 3. The RD-14 header interconnect was designed to represent either the CANDU™ 600 or the Darlington Nuclear Generating Station interconnect geometry. As previously mentioned, the header interconnect geometry was modified in 1987 and all flow stability tests performed in 1987 used this modified geometry.

The starting conditions for these tests were nominal reactor operating conditions i.e., full power (5 MW per pass), full flow (21 kg/s) and 10-MPa primary side pressure. Void was induced in the primary side by reducing the primary flow through pumps speed reductions, by reducing the primary side pressure or by increasing the secondary side pressure. Tests were performed with and without the surge tank connected to the primary side and with and without orifices installed in the header interconnect lines.

Shown in Figure 6 is a comparison of the CATHENA-predicted flow and the experimentally observed flow, for a test in this series. The onset of oscillatory flow is predicted accurately, with the oscillation period and amplitude also predicted well. This particular test is described in more detail in reference 17.

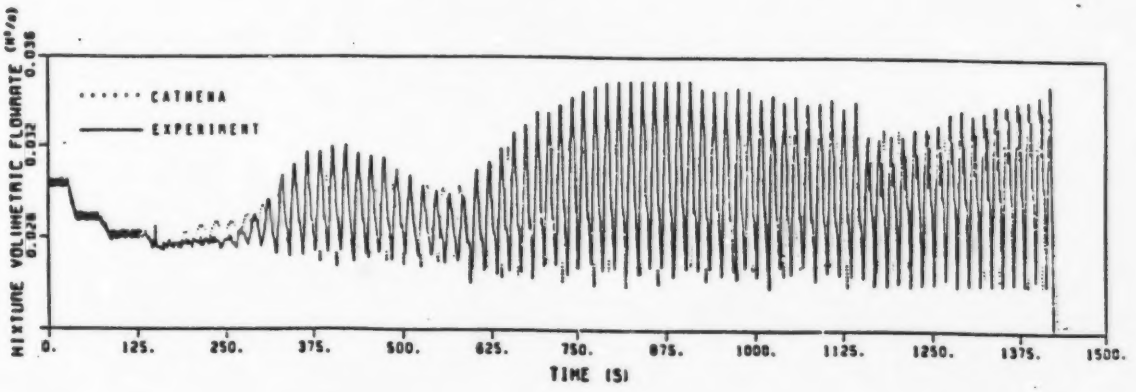

Figure 6: Channel Flow for Flow Stability Test

D. RD-14 STEAM GENERATOR

1. Introduction

As part of the CATHENA validation program, steady-state and transient simulations of selected tests from the RD-14 Steam Generator Characterization tests program were performed. The experimental program was conducted in 1986 November, following modifications to the secondary side of the RD-14 steam generators.

CATHENA was used to provide pre-test confirmation of recirculation rates expected for the downcomer orifice size installed in the facility. A sample input file can be found in the AECB-AECL proprietary report WNRE-RC-54-2.

2. Facility (RD-14 Steam Generator Modifications)

2.1 Background

When the RD-14 facility was constructed, the steam generators were designed to remove 5.5 MW of power from the primary fluid. At full-power conditions, the steam and liquid did not separate in the steam drum, and so, liquid recirculation through the external downcomer was never achieved. The steam generators behaved in a "kettle"-like manner. This proved difficult to model, since the quantity of water in the steam generator was difficult to determine, and was not reactor-typical. These problems were rectified by installing steam separators in each of the RD-14 steam generators. Installation of the spiral-arm separator maintained a liquid level above the downcomer entrance and ensured fluid flow in the external downcomer. This made the RD-14 steam generators more CANDU™-typical and simplified level measurements and modelling of the secondary side. Some of the primary-side tubes within the tube bundle were also repaired during the installation of the the separators.

2.2 General Description

A four arm spiral-arm separator was installed in the steam-drum of each of the RD-14 steam generators. The separator installed in the RD-14 steam generators is geometrically similar to a single separator module in the coarse separation "deck" of a CANDU™ 600 steam generator. The separator has been described in more detail by Hanna and Ingham[18].

2.2.1 Primary Side

The RD-14 primary system has already been described in section C-2.2.1 of this report.

2.2.2 Secondary Side

The RD-14 secondary side has already been described in section C-2.2.2 of this report with the exception of the steam drum modifications (inclusion of separators) mentioned above.

3. CATHENA Idealization

3.1 Philosophy

The idealization used for the RD-14 steam generator was designed for steady-state and operational transient simulations. Since the steam generator behaviour was of main interest, the primary system of the RD-14 facility (outside of the steam generator) was not included in the idealization. The main purpose of the CATHENA simulations was to assist in determining an appropriate downcomer orifice size for a CANDU™ representative recirculation ratio at full-power conditions. The void fraction and its profile within the steam generator and the total frictional pressure drop in the recirculation path were of principle interest in this idealization.

3.2 Primary System

Primary-side conditions were supplied through boundary conditions at the steam generator inlet and exit plenums. The boundary conditions supplied for the simulations were the primary-side inlet-plenum temperature and the primary-side mass flow rate. They were determined from the experimental results and made a function of time for the transient tests.

3.3 Secondary Side

The CATHENA secondary-side idealization includes only components within the steam generator. For the components outside the steam generator, for example, the feedwater system and jet condenser, boundary conditions were used. The boundary conditions were the secondary-side steam-outlet pressure (i.e., jet-condenser gauge pressure), and the secondary-side feedwater temperature. These boundary conditions were determined from the experimental results and were made time-dependent for the transient case. In the steady-state tests, the feedwater mass-flow rate was determined to be the rate necessary to achieve steady-state conditions at the desired steam-drum water level. In the transient experiments, manual control was used to adjust the secondary-side liquid level. As a result the steam-generator level control system in CATHENA was not used; instead, the feedwater mass-flow rate was determined from the experimental results and imposed as a boundary condition in the transient simulation.

3.4 Thermalhydraulic Idealization

The RD-14 steam generator idealization is shown in Figure 7. The idealization includes the recirculation path through the central baffle box below the top of the preheater elevation, because this may influence the void fraction distribution within the steam generator and, therefore, the recirculation ratio. The preheater was idealized as a long inclined pipe to account for the additional fluid path length around the preheater baffles. This idealization allows a more representative liquid velocity and heat transfer calculation within the preheater. It must be pointed out, however, that heat transfer coefficients appropriate to bundle cross-flow are not at present available within CATHENA.

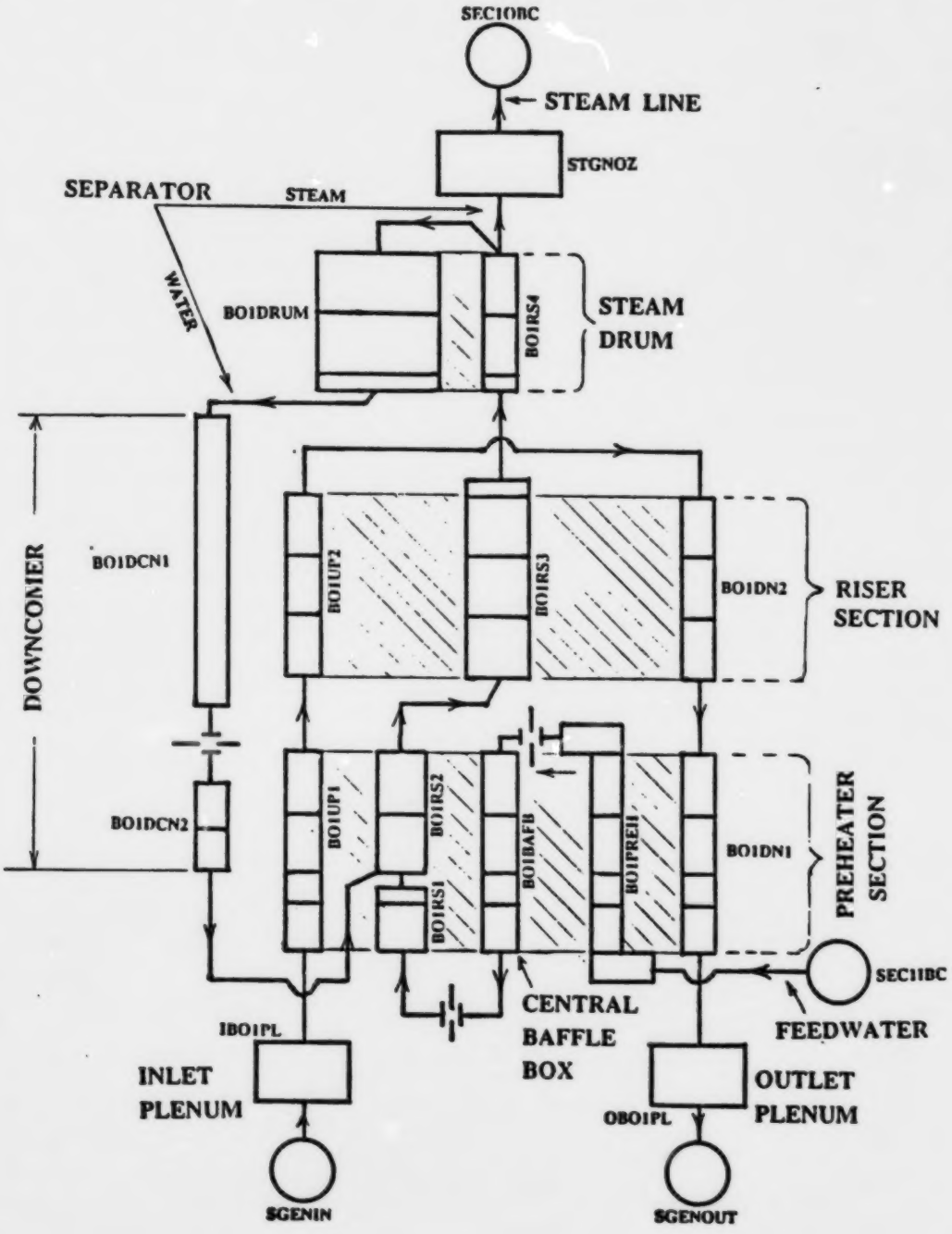

Figure 7: CATHENA Idealization of the RD-14 Steam Generators

The hot- and cold-leg of the steam generator were not separately modelled above the preheater because the holes in the central baffle box should promote good mixing. Phase separation in the steam drum was modelled by using CATHENA's separator model at two locations, a liquid separator model at the entrance to the downcomer and a vapour separator at the top of the steam drum. Both separators were assumed to be 100% efficient in the CATHENA idealization. The true efficiency of the spiral-arm separator is unknown.

4. Input File

A series of steady-state and transient steam generator characterization experiments was conducted in the RD-14 Thermalhydraulic Test Facility. The purpose of these experiments was to study the thermalhydraulic behaviour of the steam generators under normal steady-state conditions as well as over a range of conditions that might be encountered in postulated reactor accidents. Data from these tests will provide a data base to validate steam generator models in CANDU™ reactor simulation codes.

The steady-state experiments conducted examined the effects of the primary-loop flow rate, heated section power and secondary-side pressure on the steam generator. The experiments were conducted over the ranges of 1 to 27 L/s primary flow rate (typical natural-circulation flow and typical reactor full-power flow conditions), 0.1 to 5 MW per heated section power (typical decay power levels to typical full-power conditions) and at 0.1 and 4.5 MPa(g) secondary-side pressures. All experiments were carried out with single-phase conditions in the primary circuit. When the desired steady-state conditions were established, and data had been collected, the effect of steam-drum water level was examined by perturbing the steam-generator level controller to achieve a new steady-state condition.

A series of transient characterization experiments at full power and flow conditions was also conducted. In these experiments, the heated section power was tripped to CANDU™ typical decay power levels. In some experiments, the primary pumps were ramped down to simulate a loss of class IV power. In other tests, the secondary side was depressurized to simulate crash cooling.

CATHENA simulations of steady-state and transient steam generator behaviour have been reported in reference 18. Shown in Figure 8 is the CATHENA simulation of the steam generator water level transient during a power trip in the heated test sections without pump trip or secondary-side crash cooling. The qualitative agreement between simulation and experiment is good. The discrepancies shown are believed to result from the distribution of frictional losses within the steam generator bundle and the coarseness of the idealization.

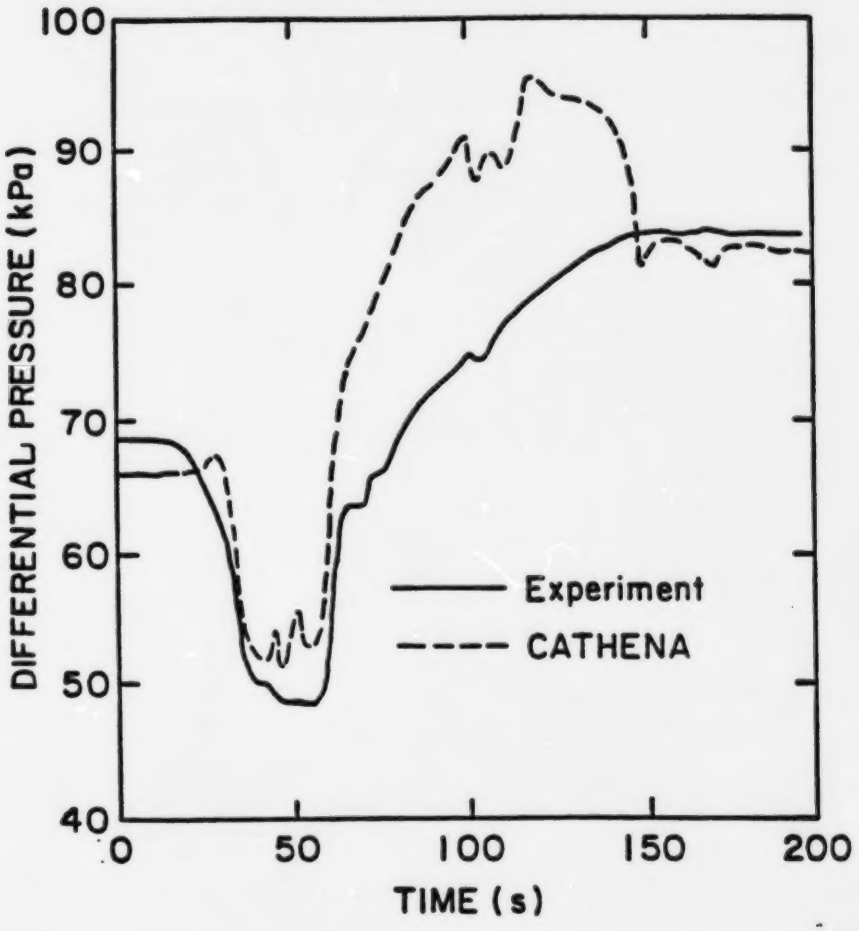

Figure 8: CATHENA Simulation of Steam Generator Water Level Transient

E. RD-12 STEAM GENERATOR BLOWDOWN TEST FACILITY

1. Introduction

As part of the CATHENA validation program the simulations of some of the RD-12 steam generator blowdown test program were conducted. The purpose of the experiments was to examine the response of measured levels in the steam generator vessel and the heat sink availability of a medium-scale steam generator following a steam-main break. The experimental program was conducted during 1985.

A sample input file for a blowdown transient can be found in the AECB-AECL proprietary report WNRE-RC-54-3.

2. Facility

2.1 Background

In CANDU™ reactors, one of the postulated upset conditions is a break in the steam-line piping of a steam generator, leading to a loss of part of the normal heat sink and a possible loss of pressure control in the primary heat transport system. The primary parameters of interest in this postulated condition are the availability of the steam generator as a heat sink during the depressurization, the response of the steam generator level instruments that form part of the reactor trip system, and the primary system's response to the depressurization.

2.2 General Description

The test facility is shown schematically in Figure 9 and has been described in reference 18.

2.2.1 Primary System

The facility used one heated channel, one set of inlet and outlet feeders and headers from the RD-14 loop at WNRE as the primary system.

2.2.2 Secondary System

The steam generator is a medium-scale, vertical U-tube (42-tube) boiler. It has a centrifugal primary steam-water separator, a perforated-plate secondary separator, an internal feedwater preheater, and an annular downcomer. These features make the experimental vessel geometrically similar to a typical CANDU™ steam generator. The steam generator was depressurized by opening a fast-acting valve in the steam line. An orifice plate, upstream of the fast-acting valve, controlled the discharge rate. For large break sizes, the discharge flowrate measuring spool piece was removed to preclude choking at the venturi meter throat.

3. CATHENA Idealization

3.1 Philosophy

The idealization of the primary system, outside of the steam generator, was done only to simulate its thermal response to the depressurization of the steam generator. Therefore, the primary system was not idealized in detail. The parameters most important were the thermal inertia and transit time of the primary heat transport system.

The idealization of the steam generator was done in fine detail. This was done for two reasons: first, the thermal mass of metal and its distribution are important parameters in a depressurization; and second, a grid-resolved solution was sought to reduce numerical uncertainties. The idealization developed here is based on the results of previous simulations (see Hanna et al.[19]), and uses a grid capable of generating a spatially converged solution.

3.2 Primary System

Figure 10 shows the primary system idealization used. The primary heat transport system used in these experiments was only a portion of the RD-14 system. No attempt has been made here to idealize the primary system in these experiments in a similar fashion to the other CATHENA simulations of experiments in the RD-14 test program.

3.3 Secondary Side

Figure 11 shows the idealization of the secondary system of the RD-12 steam generator blowdown test facility including the discharge line. The discharge line idealization shown was appropriate for the larger break sizes that had the discharge flowrate measuring spool piece removed.

4. Input File

A series of 22 experiments were conducted at the Whiteshell Nuclear Research Establishment (WNRE) in which a medium-scale steam generator was depressurized through an orifice in the steam-line piping. The purpose of these experiments was to provide information on the response of steam generator liquid level instrumentation and on the heat removal rate from the primary system during the depressurization. The series of experiments also provided a database to verify current and future steam generator models used in reactor safety analysis codes.

CATHENA simulation results for the steam generator blowdown tests have been reported in references 19 and 20.

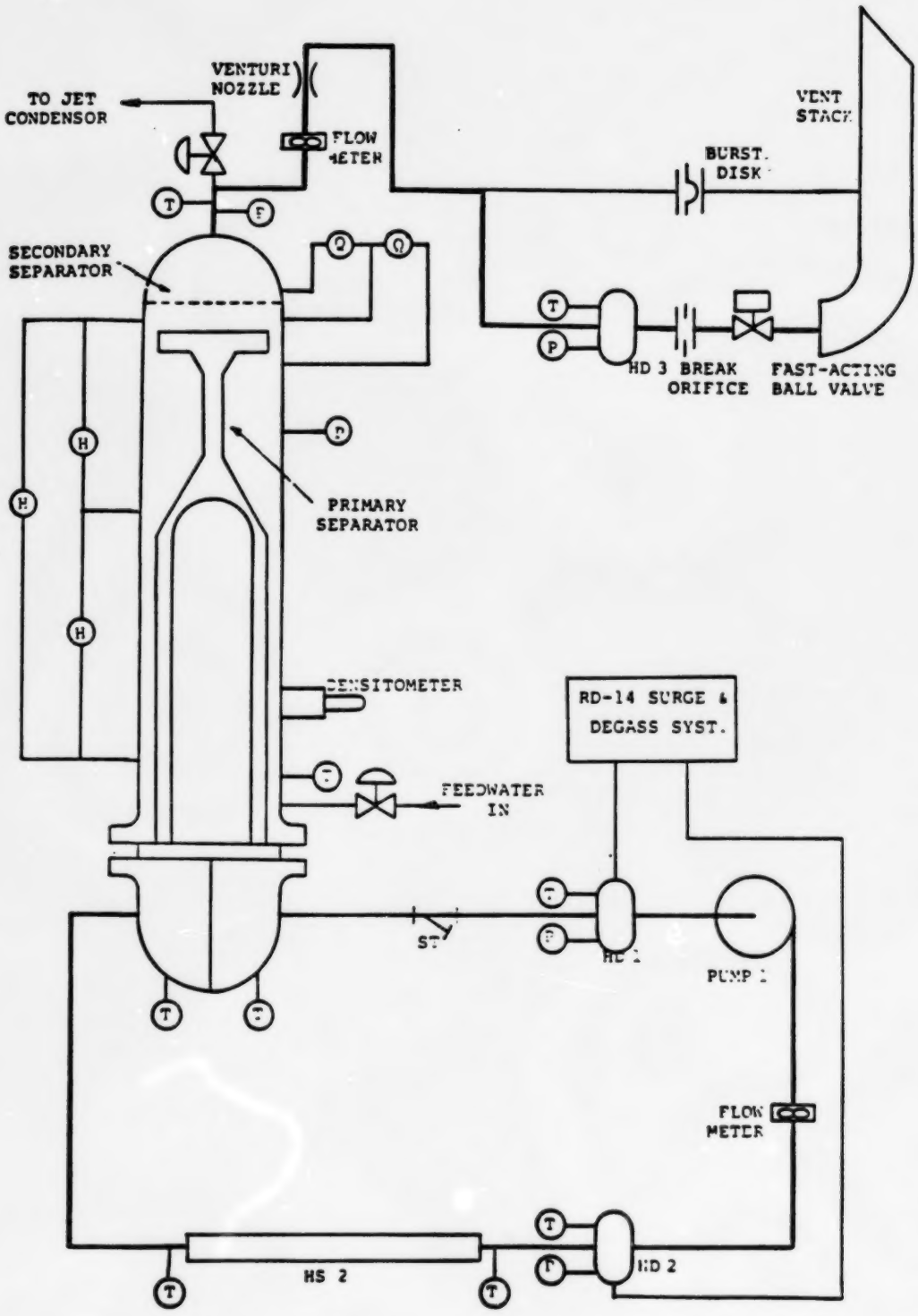

Figure 9: RD-12 Steam Generator Blowdown Test Facility

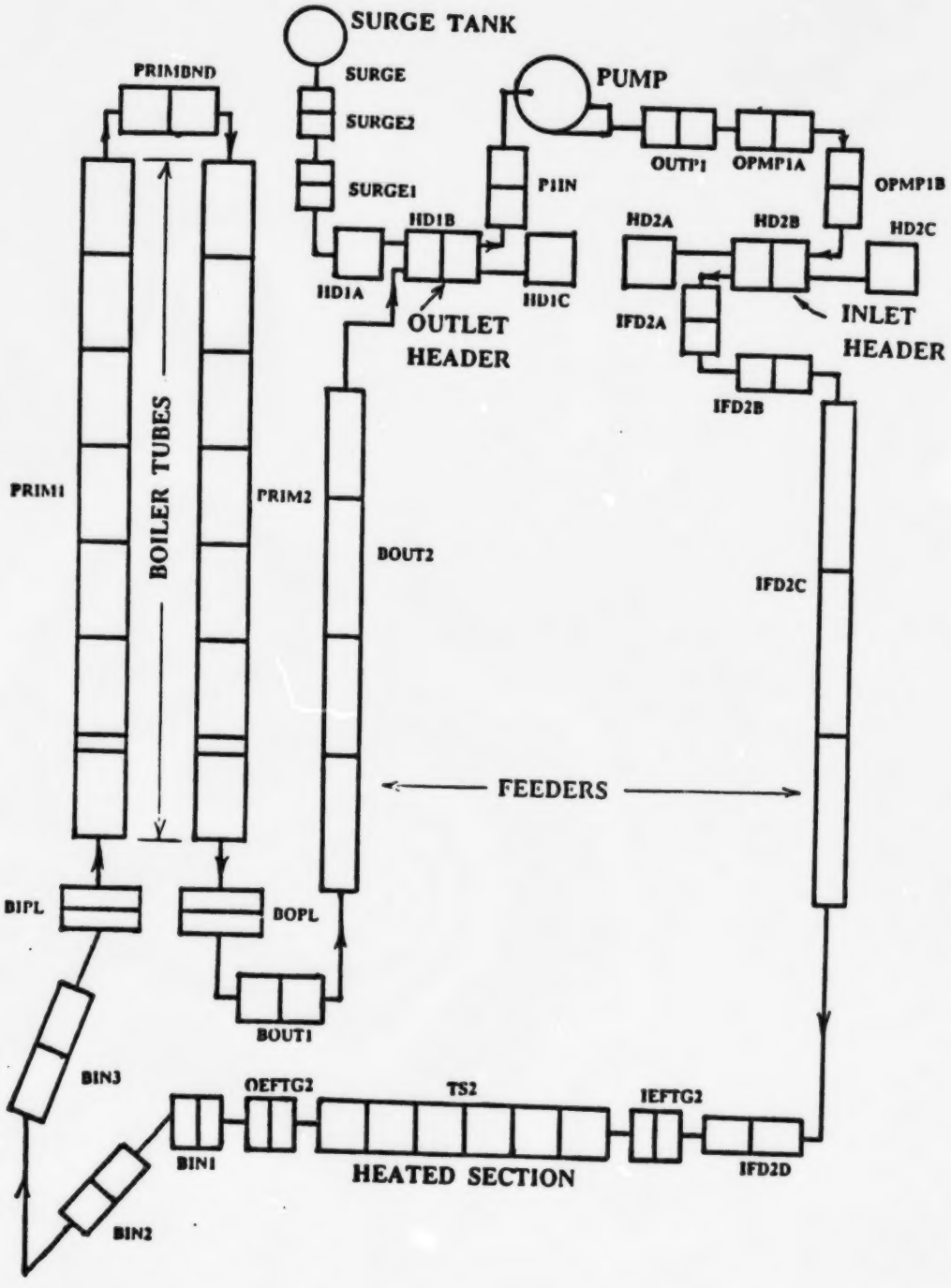

Figure 10: CATHENA Idealization of RD-12 Steam Generator Blowdown Test Facility Primary Side

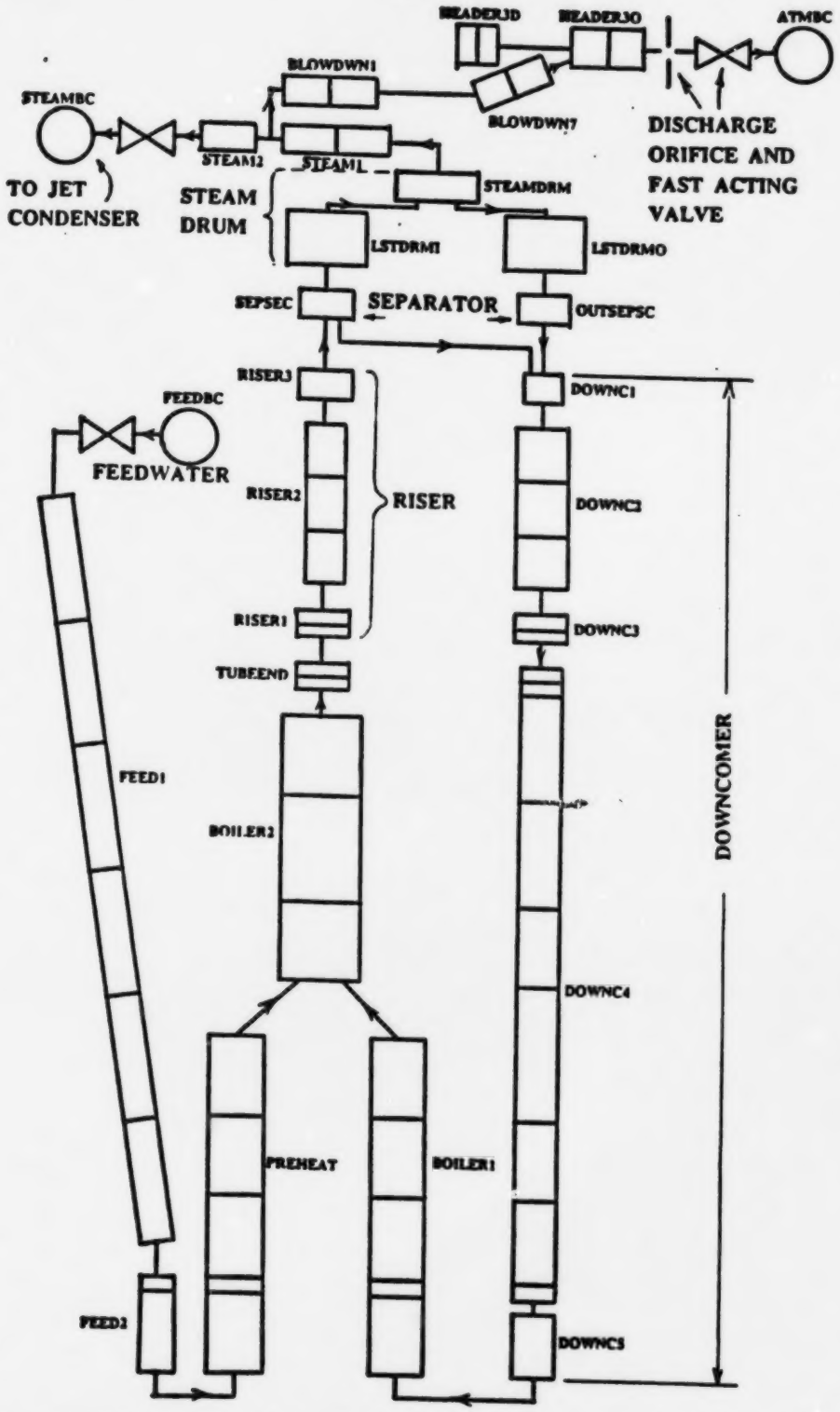

Figure 11: CATHENA Idealization of RD-12 Steam Generator Blowdown Test Facility Secondary Side

F. COLD WATER INJECTION TEST FACILITY

1. Introduction

As part of the CATHENA validation program, simulations of some of the cold-water injection tests performed on the CWIT facility were conducted. Two test series are reported in this document. The purpose of these test series was to study the effect of spray cooling the headers and feeders and initial metal temperature on header/feeder/channel refilling.

Sample input files from one test in each of the two series can be found in AECB-AECL proprietary report WNRE-RC-54-4.

2. Facility

2.1 Background

In CANDU™ reactors, one of the postulated upset conditions is a break in the inlet or outlet header of the primary coolant system. The reactor Emergency Coolant Injection (ECI) System injects cold water into the reactor headers with the ultimate objective of cooling the fuel in the core channels. The refilling phenomena of the facility and the refill time are the subjects of interest. The refill time is affected by a number of parameters: power, injection pressure, break size, initial pipe temperature, and location of the injection point (i.e., inlet or outlet, or both, headers). This facility was designed to investigate the affects of these parameters on header/feeder/channel refill.

2.2 Description

Figure 12 shows the CWIT test facility with single-channel geometry. The main features of the facility are two reactor-length horizontal heated channel assemblies, fixed elevation inlet and outlet headers, inlet and outlet feeders in reactor-typical configurations, blowdown capabilities from both inlet and outlet headers, and ECI injection to one or both headers.

The heated channels contain a 37-element CANDU™-type heater bundle with a uniform axial heat flux. Radial power depression ratios can be set for individual heater rings. End fitting simulators are connected between the channel and feeders to simulate reactor conditions.

A variety of break sizes can be simulated using differently sized orifices installed downstream of fast acting valves at the headers. Inlet header breaks and outlet headers breaks, or both, can be simulated. Discharged fluid is collected in a blowdown tank, where the vapour is condensed by spray cooling.

The facility can be preheated to 250°C using saturated water, or to 300°C using superheated steam. Spray cooling of components and non-condensible gas injection are also available.

High-pressure ECI (up to 3.0 MPa) achieved using a nitrogen pressurizing system and pumped injection (up to 6 L/s at 580 m head) are available.

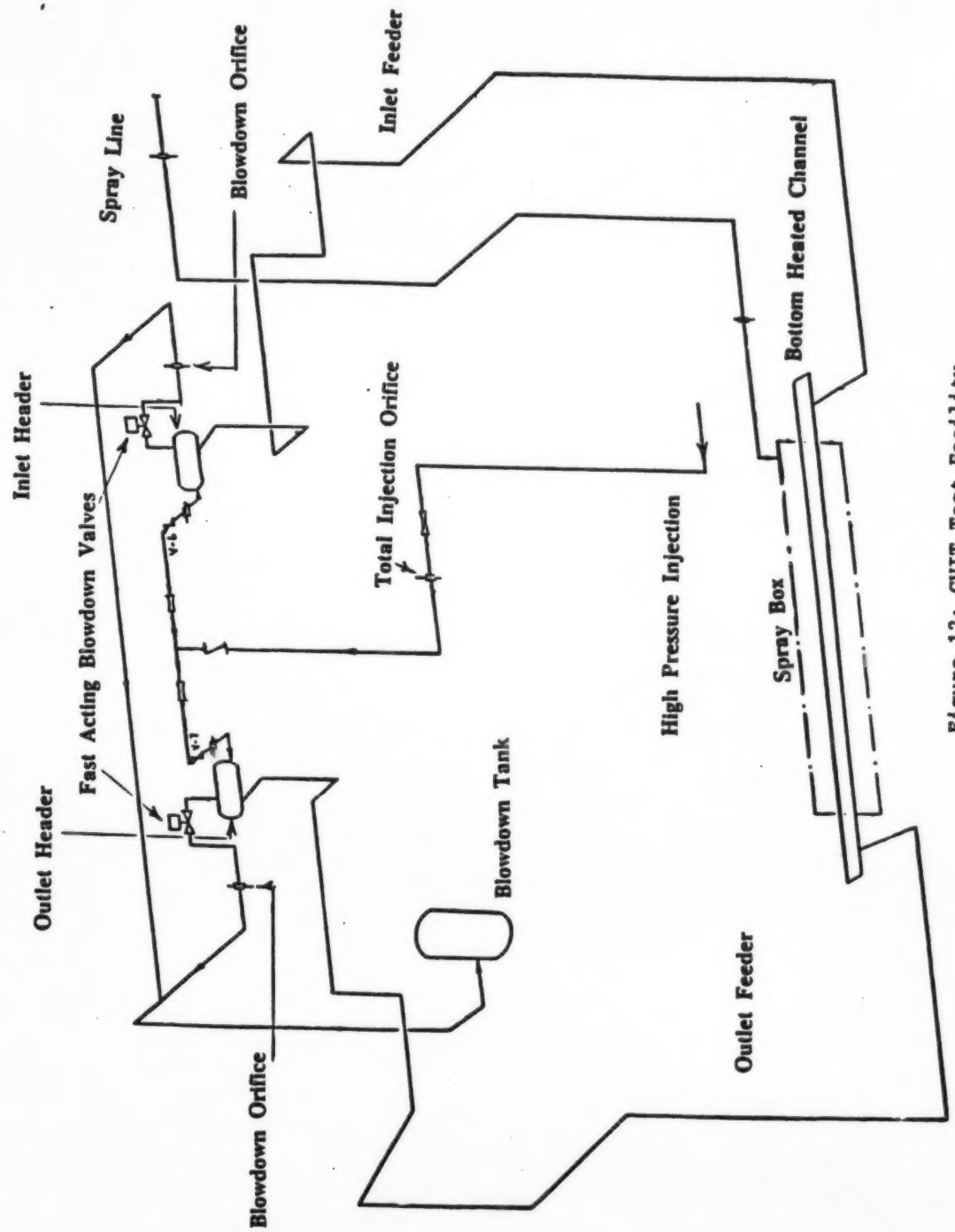

Figure 12: CWIT Test Facility

The ECI fluid temperature can be varied from approximately 20 to 100°C. ECI flowrates are varied through the installation of flow-restricting orifices. Fast-acting isolation valves, activated by pressure signals, and check valves initiate the ECI flow. Injection flows are monitored by pressure taps across venturi meters.

The facility is extensively instrumented for temperature, flow, pressure and differential pressure measurements. A Hewlett-Packard data acquisition system is used to collect, digitize, and store the data.

A more detailed description is available in reference 21.

2.3 Header/Feeder Cooling Test Series

Test series[22] 759 to 786 was performed at Canadian Westinghouse Atomic Power Division (CWAPD) 1980 November and December. This series of 26 single-channel tests was performed to study the effect of header/feeder spray cooling on refilling. These tests used only the bottom heated channel. The top heated channel was blanked off at both headers. Some of the tests had spray cooling applied to the headers and feeders. Other parameters that were altered were power, injection and blowdown tank pressures, break size, and break and injection locations (i.e., inlet or outlet, or both, headers).

A CATHENA input file prepared for test 774 was made available to the AECB.

2.4 Feeder Refill Time Delay Test Series

Test series 1081-1129 was performed at Canadian Westinghouse Atomic Power Division (CWAPD) in 1983 and reported in references 23 and 24.

This test series consisted of 47 tests designed to study the effects of initial feeder temperature, break size, and channel power on feeder refill time delay. All tests in this series are double-break and double-injection type. Some of the tests were single-channel tests and some were double-channel tests. For the single-channel tests, the top channel was blanked off at the headers and only the bottom channel was used.

Double-channel tests 1102-1127 of this series are not included. A CATHENA input file for test 1098 was made available to the AECB.

3. CATHENA Idealization

3.1 Philosophy

The idealization of the CWIT facility presented here is applicable to all the tests in the two series of tests previously mentioned. For the cases with single injection and/or single break, the appropriate branches can be deleted from the idealization.

A detailed idealization was made to capture the complicated refilling phenomena. Vertical and horizontal sections of piping are modelled separately to include the effect of pipe inclination on refilling. Some inclined pipe sections of the same diameter but differing in the angle of inclination were amalgamated into single branches. Horizontal and vertical pipe sections, however, were not combined.

The ECI piping upstream of the ECI pump and the discharge lines downstream of the break orifices were treated as pressure boundary conditions. Pressure data recorded at these locations were input to account for pressure variations from the normal settings.

The thermal mass of metal in the feeders and its distribution is important to the refilling phenomena as the cold injection water must cool the feeders before penetrating the heated channel. It is assumed that the piping in the CWIT facility is well enough insulated that heat losses can be ignored. In addition, the heat transfer models for the horizontal branches are sectored in anticipation of stratified flow conditions occurring. The CATHENA idealization for the CWIT facility can be seen in Figure 13.

3.2 Thermalhydraulic Idealization

Since the test series were designed to study the refill phenomena and refill time, it was important that the pipe flow areas, hence fluid velocities, and the piping volumes be accurately modelled. Correct fluid velocities were achieved by modelling piping of different sizes as separate branches. No amalgamating of different-diameter piping was performed. To aid in volume conservation, isolation and check valves were accurately located and the blowdown lines were modelled up to the orifices.

Elevation changes were also accurately modelled to capture hydrostatic head effects.

3.3 Heat Transfer Models

The thermal mass of metal in the facility and it's distribution affect the refill phenomena. The ECI water must cool the header and feeders before it can penetrate the heated sections. As a result, the volume of metal and the heat transfer areas in contact with the fluid must be accurately modelled. The mass of most metal parts that are welded to the piping were included in the idealization but metal parts clamped to the piping and metal far removed from contact with the fluid were not included. The metal mass was assumed to be evenly distributed along the length of the branch.

The facility is insulated and, in the absence of heat loss data for these tests, it was considered to be adiabatic. No attempt was made by the Thermalhydraulics Branch to simulate tests with spray cooling applied to the headers and feeders. This could be accomplished by the application of appropriate heat transfer coefficients and temperature boundary conditions to the affected branches.

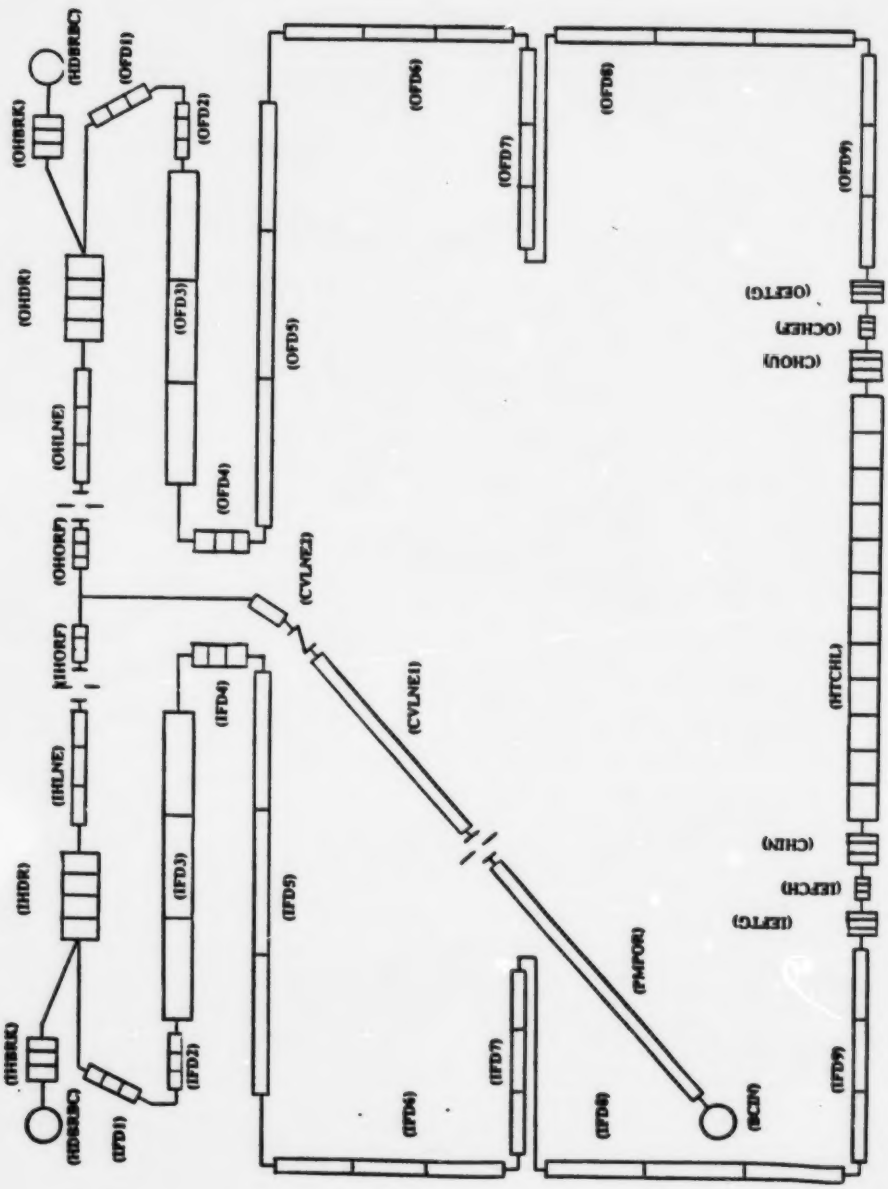

Figure 13: CATHENA Idealization of CWIT

4. Input File

A series of 26 single-channel tests was conducted to study the effect of spray cooling (applied to the headers and feeders) on refilling. These tests used only the bottom heated channel. Parameters such as power, injection pressure, break size, break location and injection location were varied. These tests provide a database to verify computer codes such as CATHENA.

CATHENA was used to simulate cases in this series that did not have spray cooling. CATHENA simulation results from one of these tests are shown below and have been reported in reference 1. Figure 14 shows the predicted and experimental pin temperature histories at the centre of the channel for an upper and lower pin. The results show that CATHENA is able to capture the stratification effect that occur in the channel. The bottom pins experience much quicker cooling (by liquid), while the upper pins continue to rise in temperature because they are exposed to steam for a much longer time.

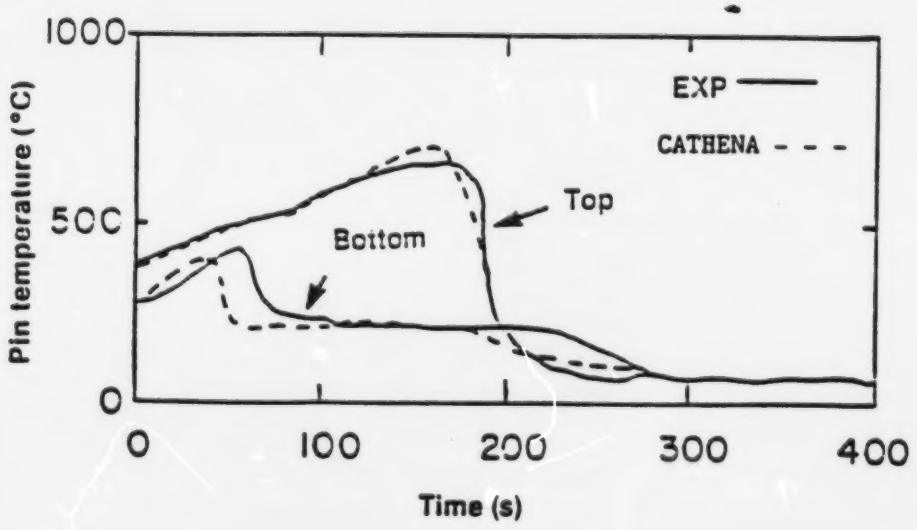

Figure 14: Upper and Lower Pin Temperature Histories at Mid Channel

G. CANDU™ 600 REACTOR

1. Introduction

As part of the CATHENA validation program, simulations of some reactor facilities have been performed. The purpose of these simulations is to compare CATHENA results to other reactor codes and in some cases actual plant data. In this way the code's ability to predict reactor events can be directly tested and its speed compared to other codes.

A sample input file for a CANDU™ 600 simulation can be found in AECB-AECL proprietary report WNRE-RC-54-5.

2. Facility

Figure 15 shows a simplified schematic of the reactor primary heat transport system. Included are the purification system and pressurizing system. The normal operating flow directions are indicated by flow arrows and the major components of these systems are labelled. Other systems such as the Emergency Coolant Injection System (ECIS), Secondary Side, Header Interconnects and Pump Seal Water Makeup System are not shown, but are included in this report.

3. CATHENA Idealization

3.1 Philosophy

Because of the complexity of the facility, detailed modelling of all individual horizontal and vertical sections of piping was not feasible; therefore, some combining of differently inclined piping and different-diameter piping was performed. As much as was possible, the correct volume, length and elevation change were used.

The CATHENA simulations resulting from the use of this idealization, were intended to be compared with other code predictions. Because of this, the idealization was prepared to be as similar as possible to the other codes.

3.2 Primary Side

Figure 16 shows the CATHENA idealization of the CANDU™ 600. The reactor's primary circuits are indicated by the heavy solid lines and the main components of the reactor primary circuits are enclosed by a dashed lines.

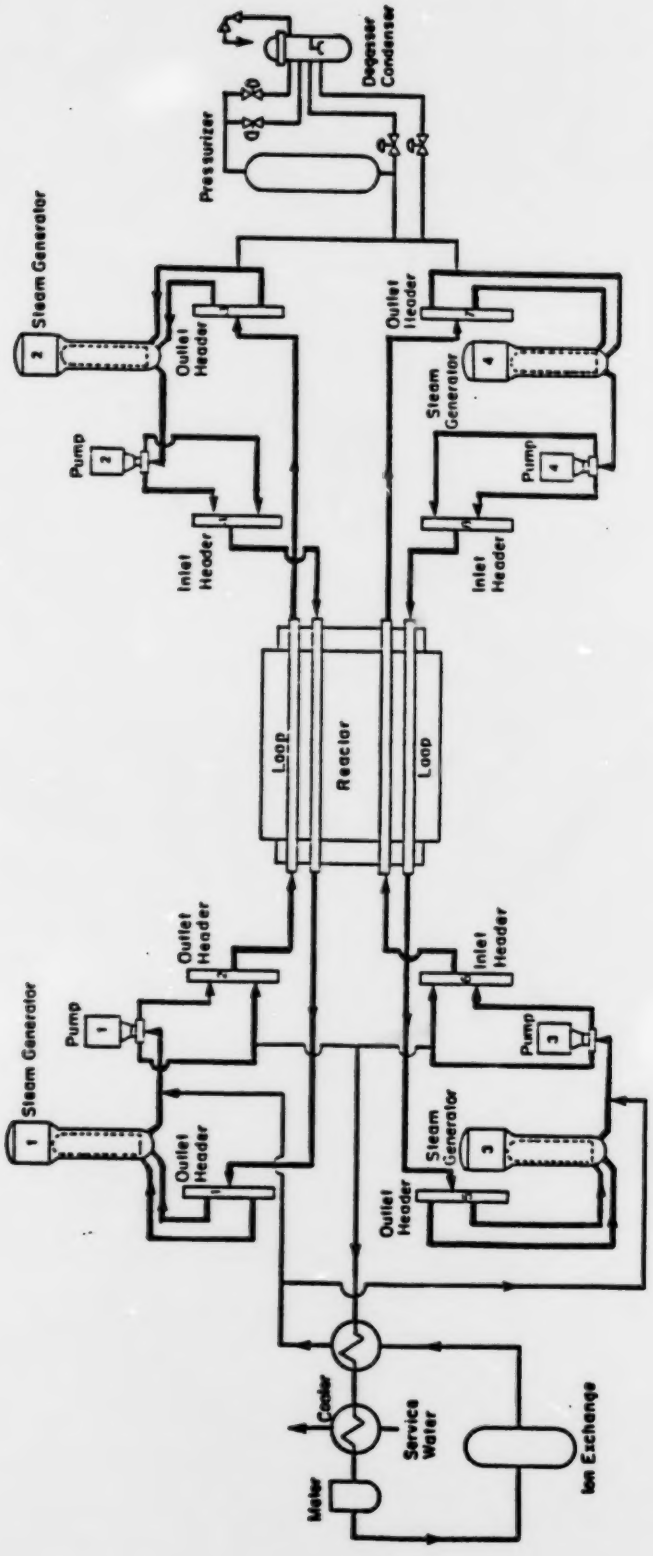

Figure 15: Reactor Primary Heat Transport System

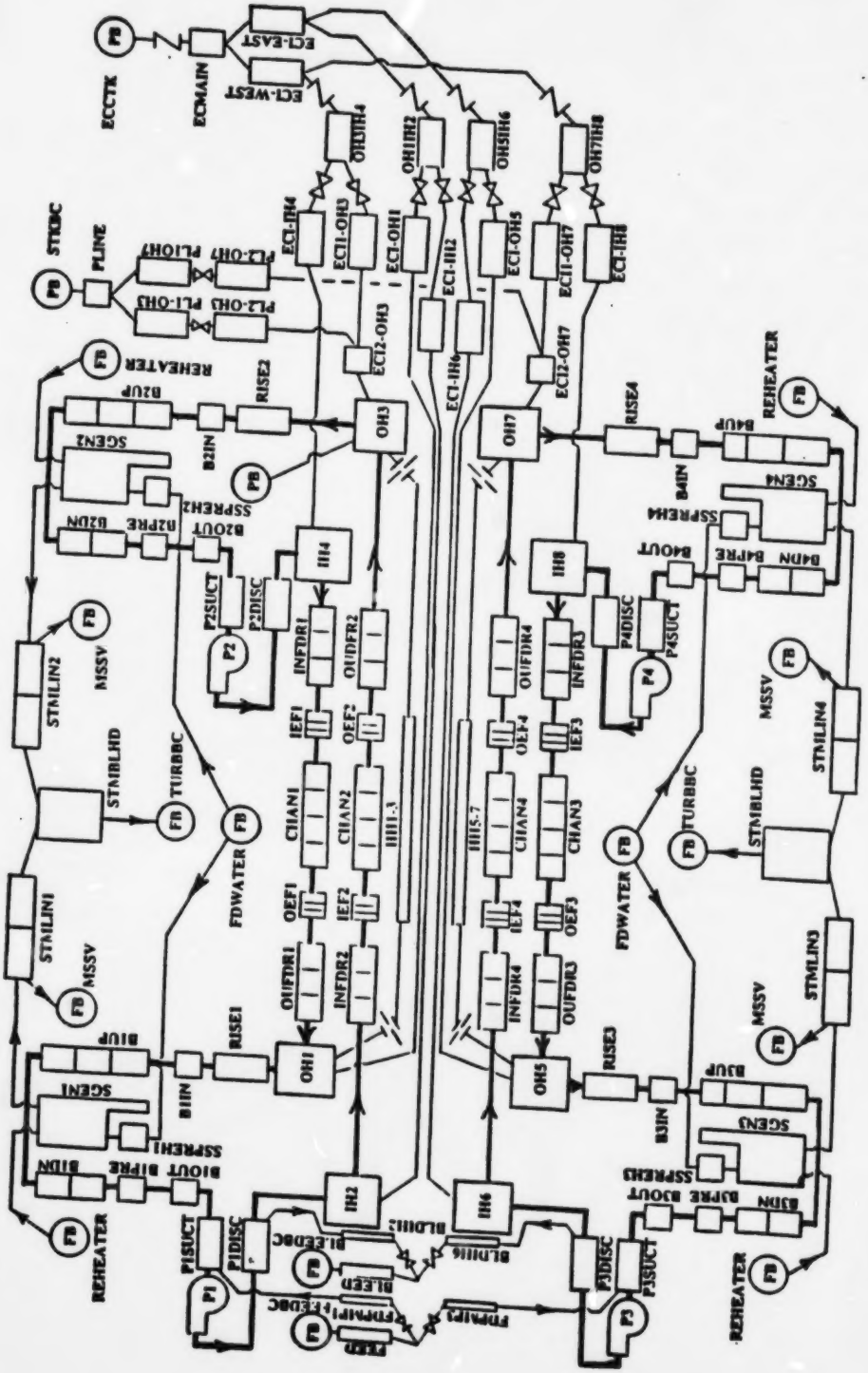

Figure 16: CATHENA Idealization of a CANDU™ 600

Included in the primary side idealization are the two header interconnects. The number designations for headers, pumps, and steam generators correspond to the primary side shown in Figure 15. Thermalhydraulic branch labels are enclosed in brackets beside the branches. Boundary conditions are designated by circles containing PB of FB, which designate pressure and flow boundary conditions, respectively.

3.2.1 Thermalhydraulics Idealization

The two primary circuits or loops are modelled. The 95 inlet feeders, 95 channels, and 95 outlet feeders connected between the inlet and outlet headers, in each of the four passes through the reactor core, are combined into single, "representative", inlet feeders, channels and outlet feeders. For system behaviour analysis, amalgamating channels and feeders into one average pass is adequate. However, for channel studies, the average pass would have to be replaced with two or more passes, with one or more of them representing an individual channel.

3.2.2 Heat Transfer Models

The heat transfer models represent the pipe walls and reactor fuel. They account for the heat transfer from the primary fluid to the pipe walls and, in the case of the steam generator tubes, from the pipe walls to the secondary side. The primary piping was assumed to be adiabatic.

The metal mass and heat transfer areas in contact with the primary fluid were made as accurate as possible. For complicated geometries (i.e., headers) the heat transfer area is not simply a product of the pipe diameter and length, but a sum of other pieces of piping (i.e., header ends, stubs) as well. Since the inside and outside diameters of the wall models are derived from the heat transfer areas and metal mass, they may differ from the actual pipe.

3.3 Secondary Side

The secondary side system was modelled from the steam generator inlet up to the outlet of the steam headers for both figure-of-eight halves of the reactor. The secondary side was modelled as simply as possible to reduce the size of the idealization.

The behaviour of the feedwater flows, reheater flows, main steam safety valves and the steam turbines were simulated by applying CATHENA's System Control Models to each of the pressure/flow boundary conditions. Thus the behaviour of the plant control systems was built into the System Control Models by means of the input data. No special user subroutines were required.

3.3.1 Thermalhydraulics Idealization

A simplified one-node boiler model with a one-node preheater (no downcomer) was used to model the steam generator secondary side. CATHENA's Steam Separator Model was used to provide separation of the liquid and steam at the boiler's steam outlet. The flows into each steam generator are treated as a flow boundary conditions, which are adjusted by the boiler level control.

Piping beyond the steam headers and beyond the main steam lines leading to the safety valves was not modelled but treated as a flow boundary condition.

3.3.2 Heat Transfer Models

No heat losses from the secondary side to the environment were included in the idealization. Only the piping metal mass of the steam generator shells was included in the secondary side idealization.

4. Input File

One of the reactor upset conditions being studied, with the aid of computer codes like CATHENA, is large loss-of-coolant accidents. An input file of a CANDU™ 600 idealization was provided to the AECB. This file was designed to perform large LOCA simulations.

H. CONCLUSIONS

Input files described in sections D to H were installed on the AECB's APOLLO computer. At the same time an up-to-date version of CATHENA was transmitted from the VAX computer system at WNRE to the APOLLO computer. Selected input files were executed on the WNRE-VAX and the AECB-APOLLO computers and compared. In all cases, results were the same (within the word-length significance of the computers).

I. RECOMMENDATIONS

Although CATHENA is written in "standard" FORTRAN, slight differences in this computer language exist between different computers. When installing a FORTRAN code (such as CATHENA) on a computer other than the one used for it's development, difficulties may be experienced. This, in fact, was the case with the CATHENA conversion from the VAX system to the APOLLO computer. Although all difficulties were resolved within 1-2 days, installation of CATHENA on a VAX computer system can be accomplished in about one half-hour. It is recommended that the AECB acquire a small VAX system in order that codes available on a VAX computer can be installed with a minimum of difficulty for use by AECB personnel.

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